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Designing a Robust and Adaptive PID Controller for Gas Turbine Connected to the Generator

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Abstract: Gas turbines are increasingly spread throughout the world to provide mechanical and electrical power in consumer and industrial sections. To ensure an accurate control process temperature of gas turbine with no extortionary operator involvement, a proper controller is required. Load frequency control of gas turbine is also regulates the power flow between different areas while holding the frequency constant. The main idea in this study is to assemble these 2 controllers in a unit work; the area of robust control has grown to be one of the wealthy in terms of algorithms, design techniques, analytical tools and modifications. Several books and papers already exist on the topics of parameter estimation and adaptive control. In The proposed approach, a robust and evolutionary based Proportional, Integral, Derivative (PID) is utilized to control frequency-response and a robust evolutionary based Proportional, Integral (PI) is utilized to control temperature. The evolutionary algorithm is used to make an optimal Proportional-Integral-Derivative (PID) controller Tuning parameters. The new robust PID controller is compared with a normal classic controller (Ziegler-Nichols) designed by the method.

Keywords: Artificial bee colony, control temperature and load-frequency, gas turbine, load disturbances, optimal control, robust control, stability analysis

INTRODUCTION

The classical wind turbines were adapted by a miller to control the area of the sails. If the mean wind speed should change, the miller could then adapt the area of the sails so that a defined torque was implemented to the grinding stone. Wind power investment worldwide is expected to expand 3-fold in the next decade (Leithead and Connor, 2000) from about $ 18 billion in 2006 to $ 60 billion in 2016 (World Wind Energy Association), (Bianchi *et al*., 2007; Geyler and Caselitz, 2007). In producing electricity from wind turbines, utilizing an operator situated at each wind turbine for the control task has become much harder in order to the necessity of dampen structural and electrical oscillations. The study on the control of wind turbines has been increased in the past few decades and as a result a number of survey papers have been leaded on the topic (Carlin *et al*., 2003). Before, references (Bossanyi, 2003) utilized Routh-Hurwitz stability criterion to derive a parametric region for stable operations. A great number of recent works have aimed at this purpose applying gain scheduling (Orelind *et al*., 1989), robust optimal control theory (Jiang, 1995), adaptive control (Malik and Zeng, 1995) and neural networks (Venayagamoorthy and Harley, 2001) to the controller design problem for hydro-turbines.

In Malik and Zeng (1995) a robust pole-shifting adaptive control technique is presented to control a hydroelectric turbine generator; mathematical development is also applied to have a robust adaptive controller (Paynter, 1955). Some of attention has been addressed at individual pitch control (Wrigh and Balas, 2004); the purpose in here is to take into account that the wind field is unevenly distributed over the rotor swept area, that is, due to wind shear, yaw error or wake from other wind turbines (Bossanyi, 2005; Leithead and Connor, 2000). In Fortunato and Camporeale (1998) an optimal controller synthesis was realized and simulated data from the nonlinear model (Hovey, 1962). Simulations applied to the both optimal controller and the originally implemented controller and finally the performance of these 2 methods are compared. General schematic of wind turbines control system is illustrated in Fig. 1. The main loop in this structure is to use the “frequency-response and temperature” to schedule the PID gains calculated for each operating point using turbine characteristics; the turbine coefficients for 5 operating points are provided below, which has the main purpose of this study to secure the stability of the system (Chaudhry, 1970). The proposed approach in this study is to design a robust PID controller based on direct PID controller adjusting based on finite number of frequency response data and temperature data and their subsequent extension to 5 operating point data. The PID parameters are chosen to supply adequate performance for unit frequency deviation in response to a load disturbance over the whole range of the operating points. The phase margin

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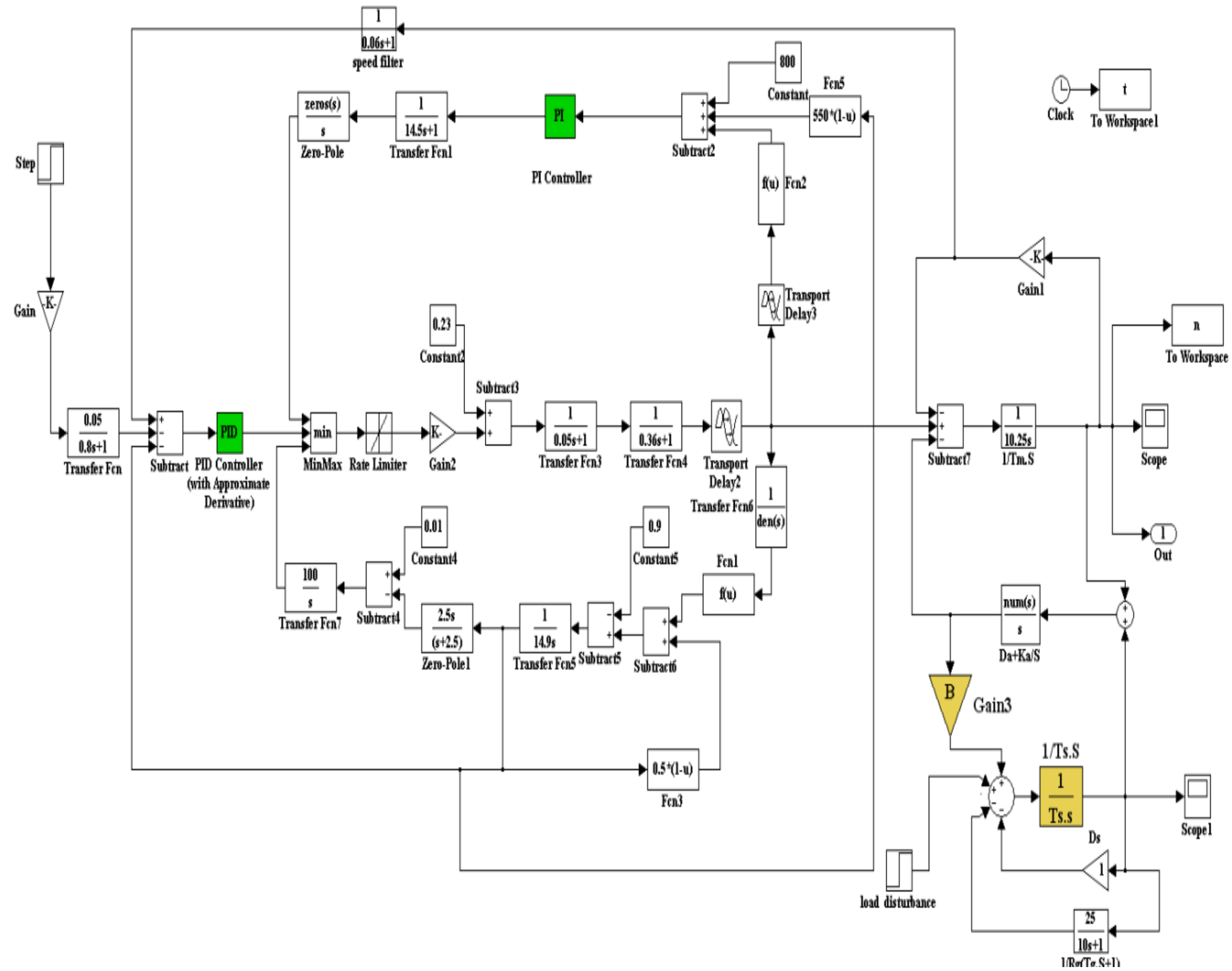

Fig. 1: Gas turbine connected to the synchronous generator and the equivalent network with control section

Table 1: The operating points for analysis gas turbine system

Case number	B (base changer)	T_s (mechanical start time of equivalent system)
1	0.12	80
2	0.16	40
3	0.20	20
4	0.14	70
5	0.18	60

and minimum gain margin for the loop of the design is guaranteed at all available operating data. The performance of a robust PID controller in which a load disturbance is injected into the unite system is investigated. To study on the performance of a simple PID controller over a single higher order controller, a robust controller is designed and its performance is compared with the simple PID controller designed earlier. In this paper Artificial Bee Colony Algorithm (ABC) is utilized to design a robust PI and PID controllers for controlling the loops of the Gas Turbine system. The results achieved from artificial bee colony algorithm are finally compared with the Ziegler-Nichols technique. Table 1 Experimental results show the high performance of the proposed technique toward the Ziegler-Nichols method.

ROBUST PI AND PID CONTROLLER DESIGN

Proportional-Integral-Derivative (PID) controller is the most commonly used control mechanism in industry today (Knopse, 2006). PID controller provides a proper design for both transient and steady-state responses, along with profitable and generic resources to real world control problems. Adding some zeros to a closed loop transfer function using differential controller, improves the transient response and Adding some poles to it using integral controller, decreases the steady state error (Chew *et al*., 1992). PID adjusting is a principle basis to have an efficient controller. PID controllers can be tuned in a different ways containing: Cohen-coon tuning, hand tuning Ziegler Nichols and Z-N step response, but these methods have some restrictions (Neenu, 2009). Frequently in practice, PID adjusting is required to experienced personnel using a trial and error procedure and some practical rules; this makes the process to have high cost and difficult activity. Evolutionary Algorithms (EAs) like GA, ICA, PSO and ABC have proved their prominence in giving better

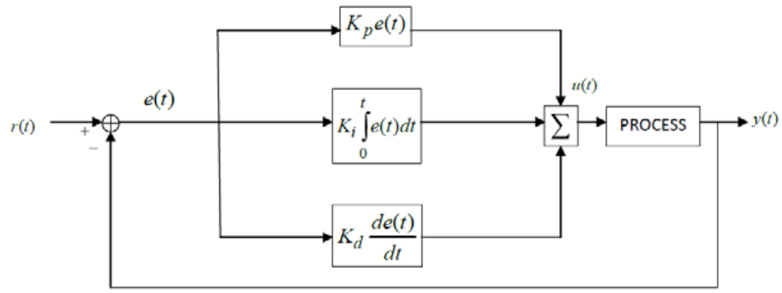

Fig. 2: PID logic control

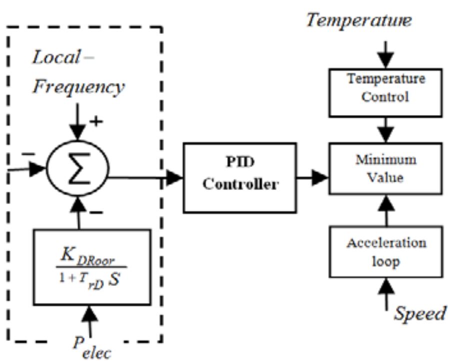

Fig. 3: Block diagram of load frequency control for gas turbine

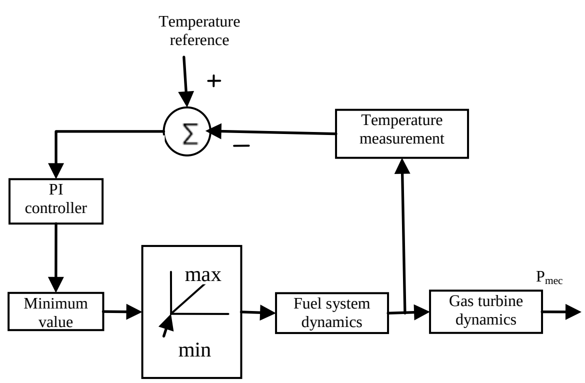

Fig. 4: Block diagram of temperature control loop

results by improving the steady states specifics and efficiency indices. In this study, Artificial Bee Colony (ABC) algorithm is utilized as an optimal design of PI and PID controller for temperature and frequency response. Some reasons for continual usage of PID are: simplicity in structure, easy to implement, principle of operation easy to understand than most other advanced controllers and premier of all, robust performance in a wide range of operating conditions. The transfer function of PI and PID controllers is presented, respectively below:

$$\frac{U(s)}{E(s)} = K_P\left(1 + \frac{1}{T_I(s)}\right) \quad (1)$$

$$\frac{U(s)}{E(s)} = K_P\left(1 + \frac{1}{T_I(s)} + T_D(s)\right) \quad (2)$$

where,
U(s) = Control signal
E(s) = Error signal
K_P = Proportional gain
T_I = Integral time constant
K_I = Integral gain
TD_D = Derivative time constant
K_D = Derivative gain

The functions of the 3 terms of a P, I and D are presented below:

- The *proportional term* (K_P which is basically the main drive in a control loop) decreases a great deal of the overall error.
- The *integral term* decreases the final error in a system.
- The *derivative term* stultifies the K_P and K_I terms when the output changes swiftly which helps decrease overshoot and ringing Fig. 2.

Main purpose of this study is to use ABC algorithm as an intelligent approach to design a suitable controller to control the load disturbances of gas turbine. Afterwards, a comparison between ABC design of PI and PID controller and standard approach of PI and PID controller defines the best method (Bryson and Ho, 1975). Figure 3 and 4 show the standard block diagram of gas turbine for temperature and load frequency control with a PID controller.

Artificial Bee Colony algorithm (ABC): Optimization subjects have grown in both aspects of size and complexity which cannot be solved using classical optimization techniques. This led to the development of heuristic algorithms. Artificial Bee Colony Algorithm is a meta-heuristic algorithm which is inspired by the intelligent explores behavior of honey bee swarms. An extended version of the ABC algorithm was then offered to handle constrained optimization problems (Karaboga and Basturk, 2007a).

The colony of artificial bees consists of three sections: employed, onlookers and scout bees; the

Table 2: The pseudo-code of the ABC algorithm

1. Initialize the population
2. Modify positions
3. Apply selection criterion
4. Repeat (cycle)
5. Allow the employed bees to share the food information with onlooker bees
6. Allow the onlooker bees to choose the best food source based on the probability calculation
7. Apply selection criterion
8. Check for an abundant solution, and (if exists) initiate a new food-source position. Otherwise, follow the next step
9. Retain best solution so far
10. Until stopping rule

Employed bees (*Eb*) randomly search for food-source positions (solutions). After the search is completed, the employed bees share the nectar amounts (solutions qualities) of the food sources and their position information with the Onlooker bees (*Ob*) on the dance area (Karaboga and Basturk, 2007b). Onlooker bees watch several dances before choosing a food-source position, according to the probability related to their nectar amount. Once onlookers and scout bees discover a new status, they may change their position to become employed bees. When the food-source position has been assayed perfectly, the employed bee associated with it pull outs it and may once more become a scout or onlooker bee. The probability *pi* of selecting a food source by onlooker bees is calculated as follows:

$$p_i = \frac{fitness_i}{\sum_{i=1}^{Eb} fitness_i} \tag{3}$$

where,

$fitness_i$ = The fitness value of the solution i
Eb = Number of food source positions or, in other words, half of the CS

In order to determine a neighboring food-source position, the ABC algorithm changes one randomly chosen parameter and keeps the other parameters unchanged which is verified as:

$$x_{ij}^{new} = x_{ij}^{old} + u\left(x_{ij}^{old} - x_{kj}\right) \tag{4}$$

where, $k \neq i$ and both are $\in \{1, 2, \ldots, Eb\}$. The multiplier u is a random number between [-1, 1] and $j \in \{1, 2, \ldots, D\}$ is randomly indexed. In other words, x_{ij} is the j^{th} parameter of a solution x_i which is selected to be corrected. When the food-source position has been unaccompanied, the employed bee associated with it changes to a scout. The scout generates a totally new food-source position as follows:

$$x_i^{j(new)} = \min x_i^j + u\left(\max x_i^j - \min x_i^j\right) \tag{5}$$

where, Eq. (5) applies to all j parameters and u is a random number between [-1, 1]. If a parameter value produced using Eq. (4) and/or Eq. (5) exceeds its predetermined limit, the parameter can be set to an acceptable value (Karaboga and Basturk, 2007a). Employed and onlooker bees choose new food sources in the neighborhood of the prior one belonging on visual information based on the comparison of food-source positions (Killingworth and Krstic, 2006). Beside, scout bees looking for a food-source position with no guidance and explore a completely new one. Scouts are specified based on their behavior, by low search costs and a low average food source quality; the pseudo-code of the ABC algorithm is presented in Table 2:

Selection of performance index: Selecting a proper performance index for minimization in the ABC algorithm is a significant problem which dictates the performance of the optimized PID controller obtained after tuning. Thereupon it is important to select a suitable performance index that accentuates the desired performance aspects such as settling time; overshoot and rise time (Killingworth and Krstic, 2006). The typical performance indices to evaluate the closed loop system response are presented below:

$$IAE = 100 \times \int |e(t)| dt \tag{6}$$

$$ISE = 10^4 \times \int e^2(t) dt \tag{7}$$

$$ITSE = 1000 \times \int t.e^2(t) dt \tag{8}$$

$$ISTSE = 10 * \int t_{sim}{}^2 \cdot e^2 dt + (100 * Us)^\wedge 2 \tag{9}$$

$$FD = (10^4 \times OS^2) + (10^4 \times US^2) + (0.0001 \times t_s{}^2) \tag{10}$$

where, Overshoot (OS), Undershoot (US) and settling time is considered for evaluation of the FD. Each performance index has its own profits and drawbacks and will result in different system performance. ISE index is an ordinary performance criterion used in a number of control usages. It tends to assess all errors with respect to the given weighting factors. ITAE index is the other criterion which has a vast application in control usages and includes the time (t) in order to penalize the settling time of the controlled system. IAE and ISE indices minimization make the overshoot decreases, but settling time increases and is seen as a drawback. Since, selection of a performance index should be based on the desired performance aspects for the overall system. Figure 5 shows comparison of the four responses.

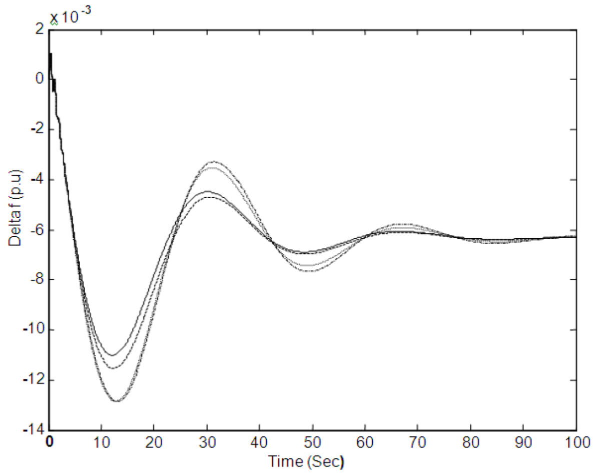

Fig.5: Comparison of performance indices: (ISTSE (-), FD (--), IAE (-.), ISE (….))

From Fig. 5 it can be seen that the response achieved with the PID parameters adjusted by using the ISTSE performance index is the best compared to the other indices. This is also in accordance with the results obtained in Killingworth and Krstic (2006). In this study, demanded performance aspects are to minimize the error and decrease the overshoot of the response. In order to determine which of the four performance indices presented before should be selected, a comparison is made based on a simple Frequency Deviation control example. A PID controller is tuned using ABC, each time using one of the four performance indices. The PID controller parameters obtained in each case is used to determine the closed loop speed response to a step change in the reference speed.

SIMULATION RESULTS AND DISCUSSION

The system is modeled and simulated in MATLAB Simulink tool. For evaluating the proposed system for optimizing of loop control in gas turbine connected to the generator, artificial bee colony algorithm is used

Table 3: Optimized value parameters of PID for load-frequency control

Symbol	K_P	K_I	K_D
ABC	1.1632	0.0305	0.0743
Ziegler-nichols	0.66	0.4950	0.2974

Table 4: Optimized value parameters of PI for temperature control

Symbol	K_P	K_I
ABC	1.7175	1.8962
Ziegler-nichols	0.8126	0.6235

(Fig. 1). Optimization process in artificial bee colony algorithm is relevant as Table 2; Turbine parameters are obtained from Hajagos (2001) Parameters used in ABC algorithm for optimizing the PI and PID controllers are presented below:

Colony size = 20
Limit = 100
Iteration = 20

And the final values for PI and PID controllers for temperature and load-frequency control respectively are presented in Table 3 and 4.

Five operating points are used from Anisha (2006) to evaluate efficiency of the proposed algorithm. Table 5 to 8 illustrate a comparison of each performance index to the other 3 on the basis of overshoot, settling time, undershoot and Figure of Demerit error utilized with and without load disturbance.
As it can be seen, the desirable value for ABC algorithm has a good result toward the Ziegler-Nichols. The desirable system is a gas turbine connected to synchronous generator and equivalent system; in the presented system, parameters include: *Base changer* (B) and *Mechanical Start* Time of equivalent system (T_s) are utilized as operating points for designing the temperature control and load-frequency control loops. Control section is applied by ABC algorithm and Ziegler- Nichols algorithm; system output frequency Sy deviation in B and T_s without spotting the load disturbances is shown below:

System output frequency deviation in B and T_s with spotting the load disturbances are shown below:

Table 5: The results of analysis gas turbine system without load disturbance for operating points

	IAE		ISE		ITSE		ISTSE	
Case No	ABC	Ziegler-nichols	ABC	Ziegler-nichols	ABC	Ziegler-nichols	ABC	Ziegler-nichols
1	2.8135	11.0986	0.2875	1.9676	0.2284	5.3472	0.4735	21.6090
2	4.1062	12.8173	0.6015	3.1356	0.5662	6.3962	1.0033	21.8997
3	3.4139	7.70220	0.4920	1.2450	0.4056	2.0058	0.5709	6.75960
4	3.3110	13.4302	0.3897	2.9013	0.3300	7.8567	0.6676	32.1301
5	4.3574	16.8939	0.6556	4.7866	0.5957	12.2106	1.1862	47.7500

Table 6: The characteristics of output response system without load disturbance for operating points

	OS		ts		US		FD	
Case No	ABC	Ziegler-nichols	ABC	Ziegler-nichols	ABC	Ziegler-nichols	ABC	Ziegler-nichols
1	0.0035	0.0035	99.9841	99.9923	0.0059	0.0080	1.4705	1.7529
2	0.0043	0.0040	99.9841	99.9960	0.0088	0.0107	1.9548	2.3145
3	0.0035	0.0033	99.9841	99.9930	0.0075	0.0081	1.6825	1.7602
4	0.0039	0.0037	99.9841	99.9950	0.0070	18.280	1.6442	1.9921
5	0.0047	0.0044	99.9840	99.9912	0.0093	0.0120	2.0823	2.6218

Table 7: The results of analysis gas turbine system with load disturbance (10%) for operating points

	IAE		ISE		ITSE		ISTSE	
Case No	ABC	Ziegler-nichols	ABC	Ziegler-nichols	ABC	Ziegler-nichols	ABC	Ziegler-nichols
1	10.1931	17.4542	3.1711	6.1512	3.6638	11.1628	7.18540	33.9419
2	13.8215	17.3981	6.5762	9.0464	6.9477	10.5227	11.5798	24.6093
3	15.1152	16.5650	9.7739	9.9255	8.3700	8.73780	11.2037	16.0529
4	17.2021	19.3638	9.3918	7.6807	10.1246	13.6683	19.6273	41.4440
5	12.6573	22.0334	5.0568	10.3943	5.7061	17.5315	10.6411	51.2524

Table 8: The characteristics of output response system with load disturbance (10%) for operating points

	OS		ts		US		FD	
Case No	ABC	Ziegler-nichols	ABC	Ziegler-nichols	ABC	Ziegler-nichols	ABC	Ziegler-nichols
1	0.0073	0.0073	99.9840	99.9913	0.0173	0.0188	4.5298	5.0738
2	0.0081	0.0079	99.9865	99.9909	0.0228	0.0239	6.8814	7.3126
3	0.0073	0.0072	99.9874	99.9888	0.0252	0.0255	7.8832	8.0191
4	0.0131	0.0076	99.9932	99.9892	0.0322	0.0204	13.1047	5.7328
5	0.0086	0.0083	99.9962	99.9898	0.0217	0.0234	6.4508	7.1797

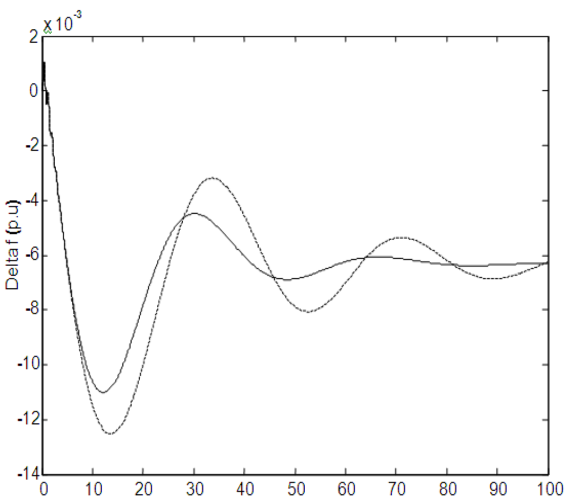

Fig.6: Frequency Deviation for operating point (1); solid (ABC), dashed (Ziegler-nichols)

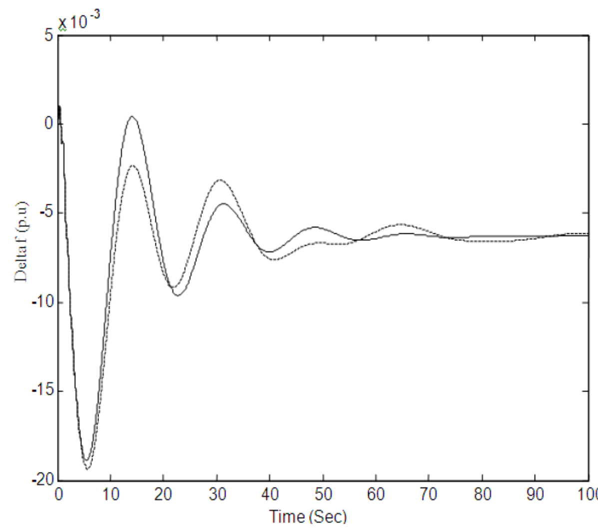

Fig. 8: Frequency deviation for operating point (3); solid (ABC), dashed (Ziegler-nichols)

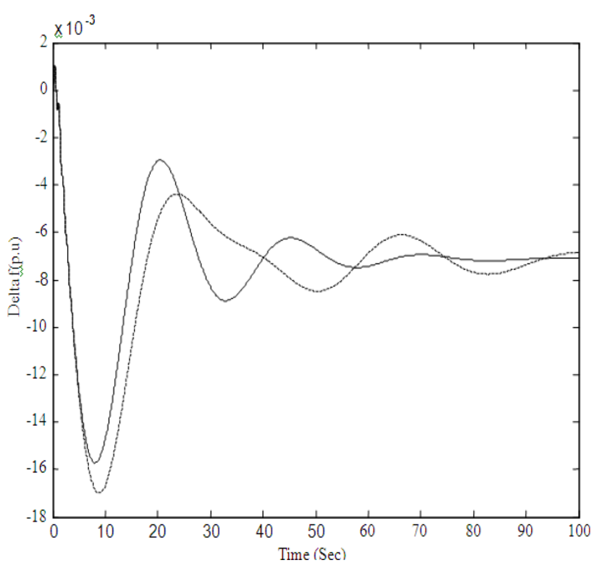

Fig.7: Frequency deviation for operating point (2); solid (ABC), dashed (Ziegler-nichols)

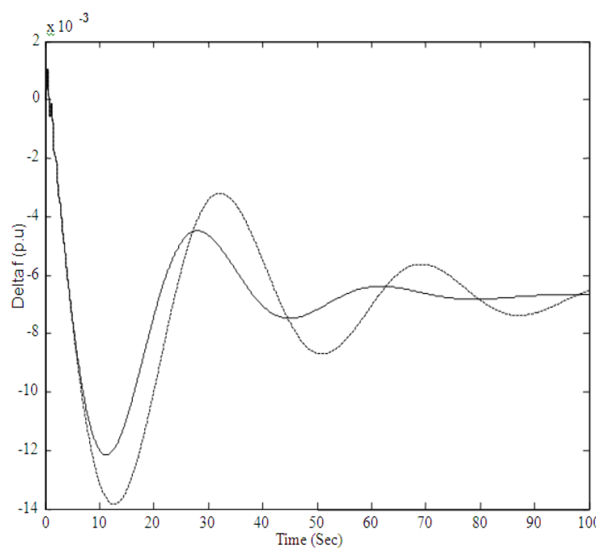

Fig. 9: Frequency deviation for operating point (4); solid (ABC), dashed (Ziegler-nichols)

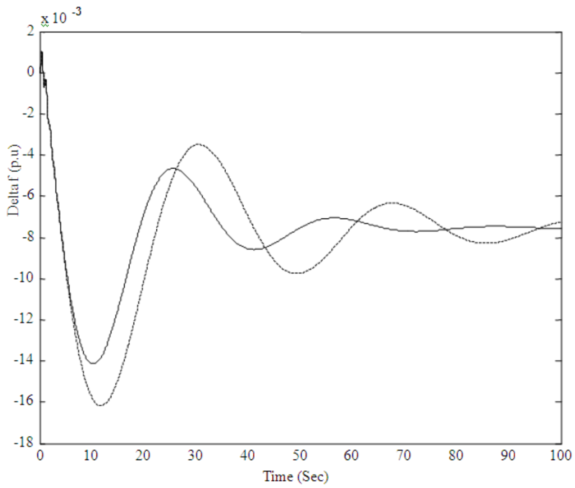

Fig.10: Frequency deviation for operating point (5); solid (ABC), dashed (Ziegler-nichols)

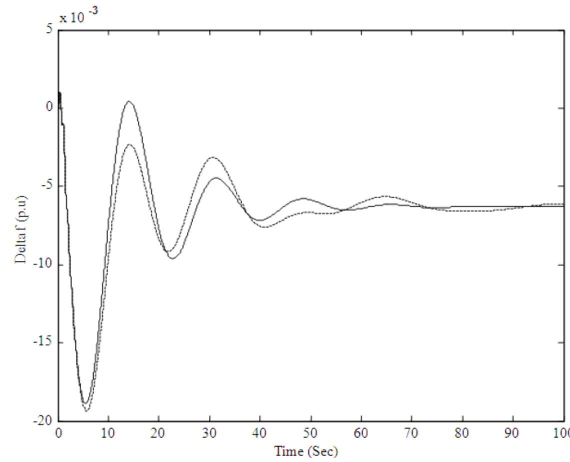

Fig.13: Frequency deviation with load disturbance (10%) for operating point (3); solid (ABC), dashed (Ziegler-nichols)

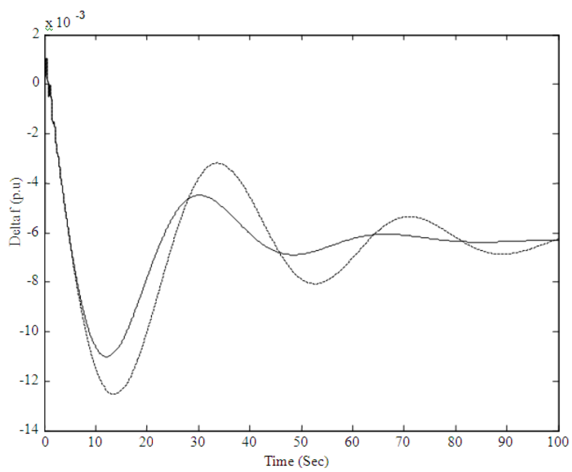

Fig.11: Frequency deviation with load disturbance (10%) for operating point (1); solid (ABC), dashed (Ziegler-nichols)

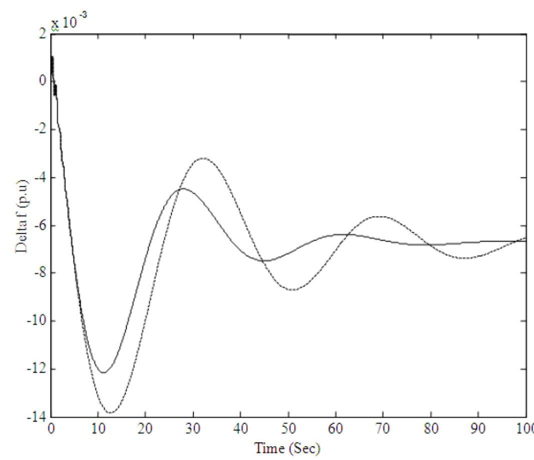

Fig.14: Frequency deviation with load disturbance (10%) for operating point (4); solid (ABC), dashed (Ziegler-nichols)

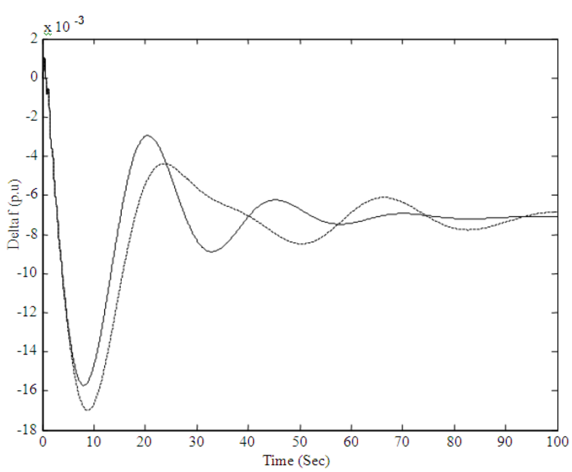

Fig.12: Frequency deviation with load disturbance (10%) for operating point (2); solid (ABC), dashed (Ziegler-nichols)

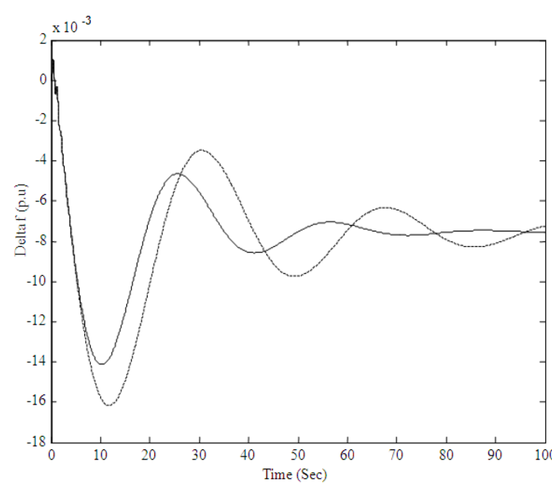

Fig.15: Frequency deviation with load disturbance (10%) for operating point (5); solid (ABC), dashed (Ziegler-nichols)

From the above, it can be seen that using ABC algorithm results a robust control for both frequency-response control and temperature control; in this evaluation, load disturbances and system operation point's changes are also considered.

CONCLUSION

In this study a new robust design based on ABC algorithm is proposed to control temperature and load-frequency loops in gas turbines connected to generator. The utilized fitness function for optimizing system is a robust function; designing of robust system is applied by considering the system operation point changes which is shown in system parameters indefinitely. In this study, after gas turbine simulating and analysis of turnover in the control system during disturbance occurs, the controllers rule is studied in system stabilization. Final results show that the proposed controller can have a high performance for designing the optimal PID controller. By comparison with PID Ziegler-Nichols controller, it shows that this method can develop the dynamic performance of the system in a better way as indicated in Table 6 and 8 and Fig. 6 to 15. The PID robust controller is the best which presented satisfactory performances and have good robustness (minimal rise time, overshoot and Steady state error which is zero).

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